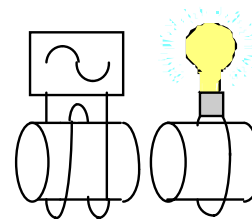**Note: Please do not place the magnets near a computer CRT at any time.** As we saw in the laboratory *Magnetic Force*, a magnetic field will affect an electron beam. Consequently, the picture on the screen will be affected. Unfortunately, because of the structure of the tube, the effects can be permanent i.e. the monitor can be destroyed.

Faraday's Law and Inductance

Introduction: One of the consequences of *Faraday's law of induction* is that if there is a *changing magnetic flux* though a circuit, there is an *emf induced* in the circuit. (The induced emf is a consequence of an electric field induced in the circuit.) The induced emf can act like a battery in that it enables charge to flow around the circuit. (Equivalently, the induced electric field pushes charge around the circuit.) Some of the most important applications of this phenomenon, of course, are associated with power generation. In the case of hydroelectric power plants, for example, falling water is used to rotate circuits so that a magnetic flux changes through them. The emfs induced in the circuits are then made available to the surrounding area via wires and are transformed to the 110V ac that is available at the wall plugs. Another application is that Faraday's Law is responsible for the operation of the inductor, an important circuit element. In this lab, we will study Faraday's law and inductors.

Theory: Faraday's law of induction can be written

Text eq. [29-2a] $\mathcal{E} = -\dfrac{d\Phi_B}{dt}$ (1)

$\mathcal{E}$ is the emf induced in a circuit and Φ_B is the total magnetic flux through any area bounded by the circuit. As you know, magnetic flux is a consequence of a magnetic field "poking through" an area and can be written

Text eq. [29-1b] $\Phi_B = \int \mathbf{B} \bullet d\mathbf{A}$ (2)

As pointed out on page 736 of the textbook, the minus sign in eq. (1) implies that the induced emf is always in a "direction" that *opposes* the original change in flux that caused it. The consequence of the minus sign in Faraday's law (eq. (1)) is known as Lenz's law. The first goals of this lab are to verify the laws of Faraday and Lenz.

If the changing magnetic flux in a circuit is caused by changes in its own current, *I*, eq. (1) can be rewritten in terms of the self-inductance, *L*, as

Text eq. [30-5] $\mathcal{E} = -L\dfrac{dI}{dt}$ (3)

$\mathcal{E}$ is the self-induced emf. A coil of wire exhibits a large self-inductance and is known as an *inductor*. An inductor is the final circuit element that we will study this semester. It should be evident that the purpose of an inductor is to oppose change in the current in a circuit. The final goals of this lab are to measure the inductance of a coil and observe how the presence of a ferromagnetic material affects the inductance.

Faraday's Law of Induction-1 Our first experiments will be to change the magnetic flux in a circuit using a permanent magnet. The part of our circuit where the magnetic flux is changing will be a 3200-turn coil. When a magnet is in motion near a coil, the magnetic field, and hence the flux through the coil due to the magnet will be changing. Consequently, an emf should be induced in the coil. We will attempt to measure that emf. The electrical part of the equipment for this experiment is shown in the next picture.
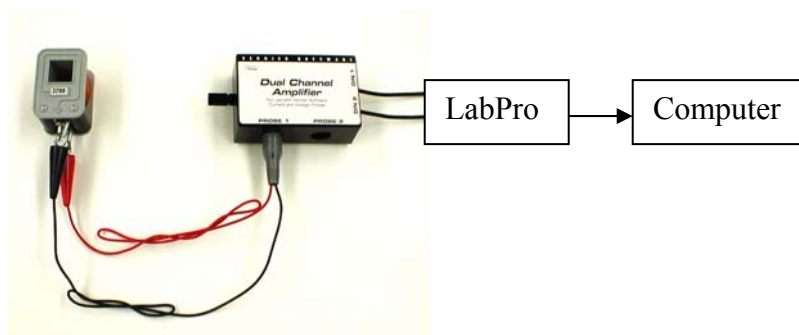

1. Plug a voltage probe into PROBE1 port of the Dual-Channel Amplifier (DCA).

2. Be sure that the appropriate leads on the DCA are plugged into CH 1 and CH 2 on the LabPro. Also be sure that the LabPro is connected to the computer.

3. On the computer, start the program **LoggerPro**. When the program starts, using the **File** pull-down menu, **Open** the folder **Far Law and Induct** then **Open** the file **Faraday1&2**.

4. Zero the voltage probe as usual by connecting the leads together then selecting **Zero** at the bottom of the **Experiment** pull-down menu.

5. Connect the two alligator clip leads of the voltage probe to one of the 3200-turn coils. For consistency, connect the leads of the voltage probe as shown in the previous diagram (red lead on the "bottom"). (Note that only one of the two "jaws" of the alligator clip fits into the banana plug receptacles on the coil.)

6. Prepare to move a magnet quickly from a position far from the coil to a position such that the *North* (**N**) pole of the magnet is near the square opening in top of the coil. We will leave the magnet there for a few seconds then move it away from the coil. Click on **Collect** and carry out this operation.

R1: Depending on the instructions from your instructor, either **Print** the graph or **Copy** the graph and **Paste** it into an **Excel** spreadsheet so that the upper left corner is in cell A1. If you are using **Excel**, resize the graph so that the right edge does not extend beyond column J.

R2: Annotate the graph with the motion and position of the magnet. (This can be done in **Excel**.)

R3: Do your results confirm the prediction of eq. (1) that an emf is induced only when the magnetic flux is *changing*? Explain.

7. Next, let us decide whether Lenz's law correctly predicts the sign of the induced emf. Look carefully at the coil and decide whether the next sketch of the cross-section of the coil correctly depicts the "direction" of the windings.

R4: Does the sketch correctly describe your experiment?

R5: If a resistor were connected between the terminals of the coil in the sketch, would the current be from **a** to **b** or **b** to **a**?

Sketch of side view of 3200-turn coil
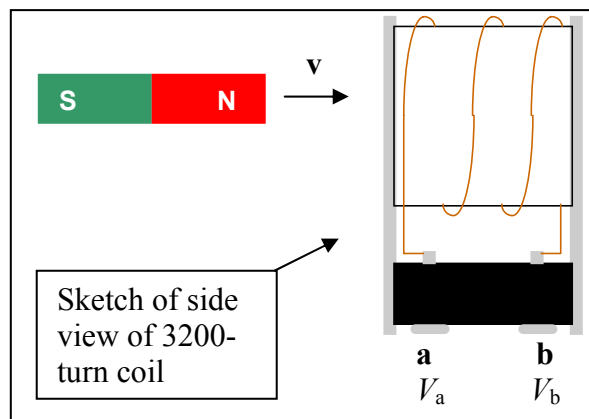
R6: For the experiment shown in the sketch, discuss whether V_b - V_a should be positive or negative.

R7: Do your data confirm this result? (If the sketch correctly describes your experiment, then the voltage should have the same sign as predicted in R6. If the connections to the coil are opposite, the voltage will be the opposite to that predicted.)

R8:   On the graph, sketch the magnetic flux vs. time. The sketch should be qualitatively consistent with the emf vs. time data. (The sketch can be done in **Excel**.)

8. Carry out the same experiment described above except move the magnet slowly. Do not print the results.

R9: Describe the difference between these results and the results obtained when the magnet is moved quickly. Discuss how your results can be explained by eq. (1).

9. The possibility always exists that the magnet that you have been using is not "good." A "good" magnet is one with approximately equal strength North and South poles at opposite (and correct) ends. A magnet will deteriorate if it is dropped or "remagnetized." Since the magnet that you have using is fairly new, it is unlikely that it is "bad." However, let us check it out anyway. Carry out the experiment described in step 6 except move the magnet quickly from a position far from the coil to a position such that the **South** (**S**) pole of the magnet is near the square opening in the coil. The emf should reverse and should have the correct sign. If either

does not occur, consult your instructor since we would like to identify any "bad" magnets and throw them away.

Faraday's Law of Induction-2 The equipment for this experiment is shown in the next picture. The only difference between this setup and that used for the previous experiment is a plastic tube that is used to guide the magnet through the center of the coil.

1. Place the clear plastic tube through the coil and orient the tube at an angle with respect to the horizontal. The angle is not critical. The purpose of the angle is to slow the magnet somewhat. Prepare to drop the magnet through the tube and coil. Nominate someone in your group to catch the magnet when it leaves the tube.

*   **Please try to keep the magnets from falling on a hard surface or coming into contact with another magnet. Again, both processes can decrease or change the magnetization i.e. destroy a "good" magnet.**

LabPro
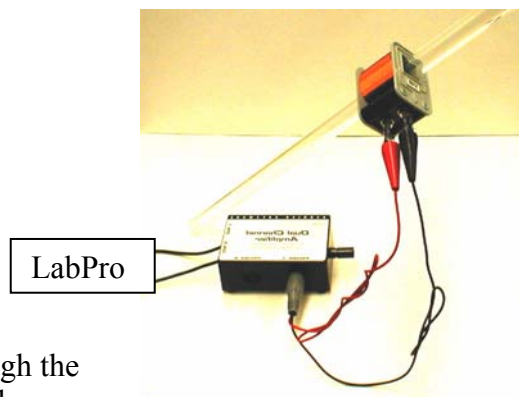
2. Click on **Collect** then drop a "good" magnet through the coil. **Manually scale** the *x*-axis so that the shape of the curve is visible.

R10: Depending on the instructions from your instructor, either **Print** the graph or **Copy** the graph and **Paste** it into an **Excel** spreadsheet so that the upper left corner is in cell K1. If you are using **Excel**, resize the graph so that the right edge does not extend beyond column T.

R11: Explain the shape of the emf vs. time data. As part of your explanation, on the graph, sketch the magnetic flux vs. time. Your sketch should be qualitatively consistent with the emf vs. time data.

3. Determine the total area under the emf vs. time curve. As you know, the computer can be used to calculate the area. First, highlight the portion of the data to be analyzed by holding down the button on the mouse and dragging the cursor across the data.   Second, select the **Integral** option under the **Analyze** pull-down menu. The total area should be zero.

R12: Is the area under the curve zero to within the uncertainty? _____ Discuss.

This result is profound. A verifiable, non-zero area under such a curve has never been found. If it were found, it would imply the existence of a magnetic monopole and this would violate a fundamental law of physics.

Faraday's Law of Induction-3 It is difficult to make a quantitative evaluation of eq. (1) using magnets. A more reliable and reproducible way of checking eq. (1) is to use a magnetic field created by a current. In the experiment that follows this one, we will vary a known magnetic field through a coil of known area so that we can predict the magnitude of the induced emf. Of course, we will also measure it. However, before we do that, we will carry out another experiment that should enable us to again verify that the induced emf is proportional to the rate of change (derivative with respect to time) of the magnetic flux and opposes the change that produced it.

1. Connect a second voltage probe to the DCA.

2. Open the file **Faraday3**.

3. **Zero** both voltage probes.

4. Set up the equipment as shown in the next diagram. Be sure to make the connections exactly as shown. Note that the DCA is grounded to the digital function generator.

The purpose of the digital function generator is to apply a triangular (vs. time) voltage to the coil on the left. Consequently, there will be a triangular current in the coil on the left. This current (The current in the coil on the left) then produces a triangular (vs. time) magnetic field and hence (changing) magnetic flux in the coil on the right. Consequently, an emf should be induced in the coil on the right. We will measure both the *voltage applied* to the coil on the left (sometimes known as the primary) and the *emf induced* in the coil on the right (sometimes known as the secondary) so that two voltage probes are required.

5. Place a rod of ferromagnetic material (approximately 2 cm x 2 cm x 8 cm) through the cores of the coils. This increases the strength of the magnetic field inside both coils. The purpose, of course, is to increase the emf induced in the coil on the right thus making it easier to measure.
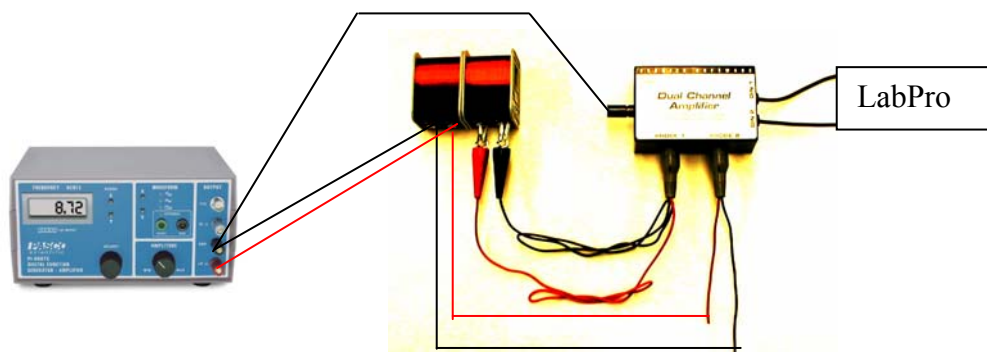
(Note the relationship between this experiment and the sketch at the upper right hand corner of the first page of this write up. In principle, for our experiment, the emf induced in the coil on the right could be used to light a light bulb.)

6. On the digital function generator, carry out the following steps.

a. Turn the AMPLITUDE to zero (fully counterclockwise) then turn it on. (There is a switch on the back.)

b. Push the RANGE ▼ button twice then set the frequency at 1.000 Hz via the ADJUST knob.

c. Press the WAVEFORM ▼ button once so that the small, green light beside the symbol for the triangular wave ⌄ lights.

7. Click **Collect** on the computer then adjust the AMPLITUDE on the Digital Function Generator-Amplifier until Voltage 2 is a triangular waveform with a maximum of about 5 V. (Note that because of the way that we have wired the circuit, Voltage 2 is the voltage in the coil on the left, the primary.) If you are not able to obtain a triangular waveform on the computer for Voltage 2, consult your instructor.

8. Click **Collect** again to take what should be the most interesting data of the semester.

R13: Depending on the instructions from your instructor, either **Print** the graph or **Copy** the graph and **Paste** it into an **Excel** spreadsheet so that the upper left corner is in cell U1. If you are using **Excel**, resize the graph so that the right edge does not extend beyond column AD.

R14: Carefully compare the shapes of the two curves and discuss whether you have results that confirm Faraday's law and Lenz's law qualitatively. (You should be able to comment both on the shape of the induced emf (Voltage 1) vs. time curve and on the sign of the induced emf.)

9. Double the frequency (Set the frequency to 2.000 Hz.) and rerun the computer program.

R15: How does the magnitude of the emf induced at 2 Hz compare with the emf induced at 1 Hz? Explain.

10. Press the WAVEFORM ▲ button once so that the small, green light beside the symbol for the sine wave, ∿, lights. Click **Collect** to take data.

R16: Explain why the shapes of the two curves are the same. How are the two curves different?

11. Remove the iron core. Click **Collect** to take data.

R17: Is the induced emf observable without the iron core? Discuss.

Faraday's Law of Induction-4 Finally, we will make a more quantitative check of eq. (1). What we will do is use a large coil to produce a known, changing magnetic field. We will then place a coil of known (approximate) area in the changing magnetic field. Consequently, we will be able to calculate the rate of change of flux and hence predict the induced emf. Finally, we will measure the induced emf and compare it with the predicted value.

Theory The magnetic field is provided by a 200-turn coil of radius R and carrying a current I. The coil is shown in the next picture. As is shown in Example 28-10 on page 720 in the textbook, the magnitude of the magnetic field at the middle of a single loop of radius R is given by

$$B = \frac{\mu_0 I}{2R} \tag{4}$$

so that for our coil

$$B = \frac{100 \mu_0 I}{R} \tag{5}$$

Consequently, if the current in the coil changes at a rate dI/dt, the magnetic field changes at a rate

$$\frac{dB}{dt} = \frac{100 \mu_0}{R} \frac{dI}{dt} \tag{6}$$

We will put a 3200-turn coil at the middle of the big coil. Since the emf induced in a coil with N turns is

Text eq. [29-2b] $$\mathcal{E} = -N \frac{d\Phi_B}{dt} \tag{7}$$

and since $$\Phi_B = BA \tag{8}$$

it follows that the emf induced in the 3200-turn coil is

$$\mathcal{E} = -\frac{0.128 \pi A}{R} \frac{dI}{dt} \tag{9}$$

We will attempt to show that this equation gives the correct value for the magnitude of the induced emf.

Experiment

1. Assemble the equipment as shown in the next picture. (Be sure to ground the DCA to the digital function generator.) Note that we will be measuring the current in the big coil (the

current from the function generator) rather than the voltage. Again, this current (in the big, 200-turn coil) is responsible for creating the magnetic field that is experienced by the small, 3200-turn coil.
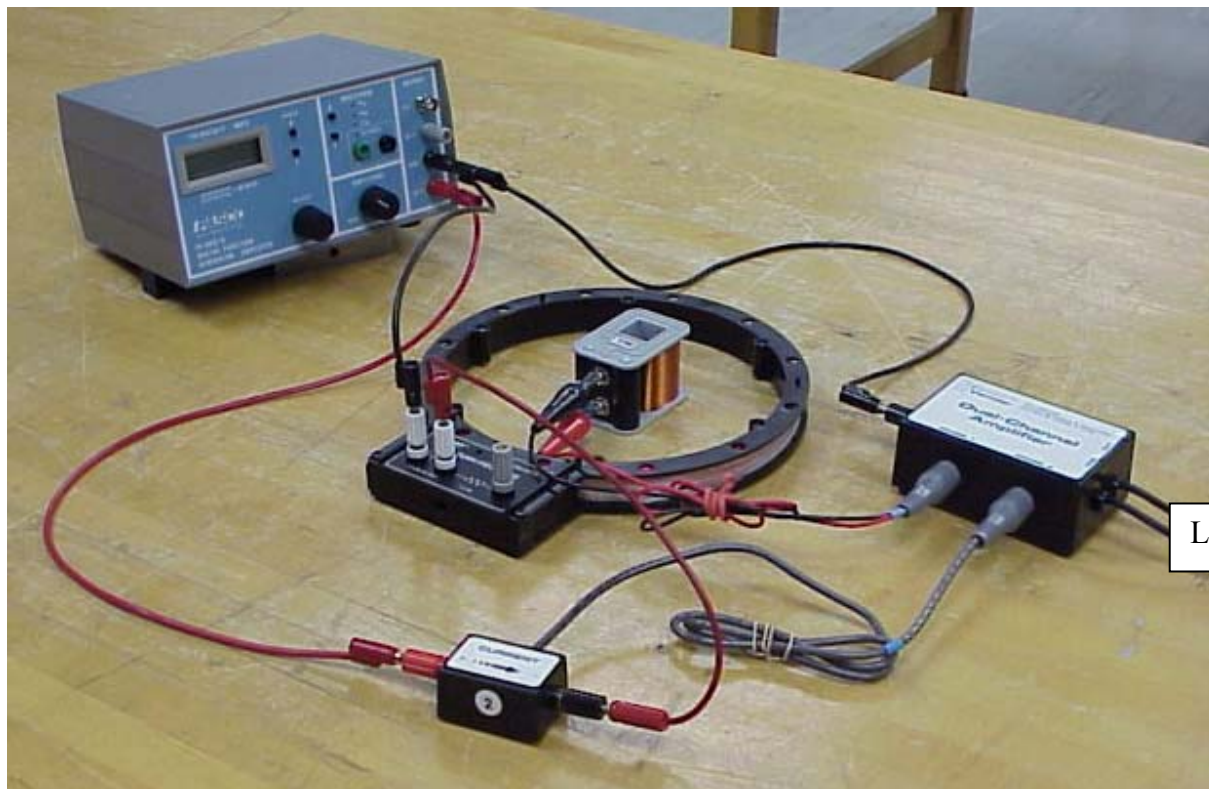
2. Open the file **Faraday4**.

3. With the voltage probes connected together and nothing connected to the current probe, **Zero** the probes.

4. ADJUST the function generator at 5.000 Hz and continue using the triangular WAVEFORM. If necessary, change the AMPLITUDE so that the function generator is supplying a maximum current of about 0.5 A

5. Click **Collect** on the computer program to record the current in the 200-turn field coil and the emf induced in the 3200-turn inductor.

R18: Depending on the instructions from your instructor, either **Print** the graph or **Copy** the graph and **Paste** it into an **Excel** spreadsheet so that the upper left corner is in cell AE1 of an **Excel** spreadsheet. If you are using **Excel**, resize the graph so that the right edge does not extend beyond column AN.

6. From the graph (or the computer), determine the average value of the magnitude of the rate of change of the current and the average magnitude of the induced emf over one half-cycle and

record the values in the space provided.

R19: $\left| dI/dt \right|$ = _____ ± _____ A/s

R20: $\left| \text{emf}_{\text{experimental}} \right|$ = _____ ± _____ V

7. Next, in order to use eq. (9), we need a value for the area, A, of the 3200-turn coil. The structure of the coil is as follows. An end view of the coil is shown in the next diagram. Measure the outside dimension of the coil, d_{outer}, and record the value in the space provided. Calculate the outside area of the coil assuming a square cross-section and record the value as A_{outer} in the space provided.

8. There are 20 layers of wire where each wire is 0.25 mm in diameter. From this information, determine the inside dimension of the coil, d_{inner}, and record the value in the space provided. Calculate the inside area of the innermost wires and record the value as A_{inner} in the space provided.

d_{outer}

R21: d_{outer} = _____ ± _____ m

R22: A_{outer} = _____ ± _____ m^2

20 Layers each
0.25 mm thick

d_{inner}

R23: d_{inner} = _____ ± _____ m

R24: A_{inner} = _____ ± _____ m^2

9. Calculate the average area, and record the value in the space provided. We will approximate the area of the coil by this average value of the area.

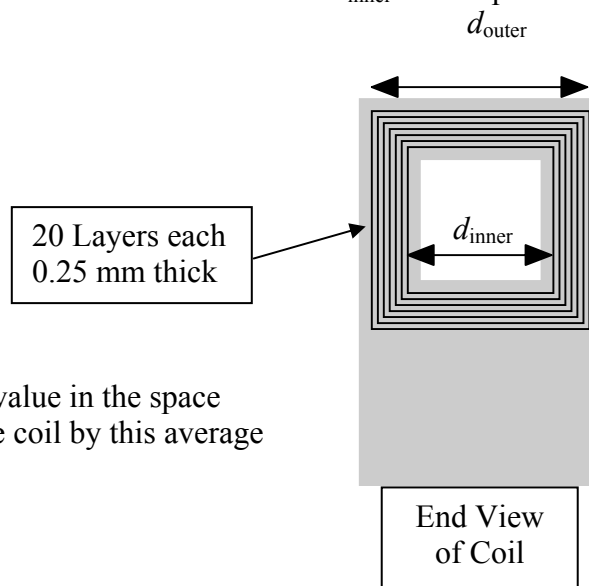R25: $A = A_{\text{ave}}$ = _____ ± _____ m^2

End View
of Coil

10. Next, determine the radius, R, of the 200-turn field coil (It is probably written on the coil.). Record the value in the space provided.

R26: R = _____ ± _____ m

11. Use eq. (9) to calculate the theoretical value of the induced emf. Record the value in the space provided.

R27: $\left| \text{emf}_{\text{theoretical}} \right|$ = _____ ± _____ V

R28: Compare the experimental and theoretical values of the induced emf.

Self-Inductance As you know, our 3200-turn coil is an example of an inductor. In order to increase our familiarity with inductance, L, and the relationship between the magnitude of L and the physical size of a coil, let us measure the inductance. Use the Pro-Tek multimeter to measure the inductance. (Turn on the meter, turn the dial to the capacitance/inductance symbols then push the FUNC button.) Record the value in the space provided

R29: $L_{measured}$ = _____ ± _____ H

Unfortunately, because of the shape of the coil, a prediction of the inductance is beyond the scope of this course. Also, there is no "accepted" value. However, we have learned something by this exercise in that we have found that the inductance is small for a relatively large coil. To understand how inductance can be increased, slowly insert the square ferromagnetic rod from part 3 of this lab into the core of one of the inductors while measuring the inductance.

R30: Describe what happens to the inductance as the ferromagnetic material is being added to the inductor.

End of Lab Checkout Before leaving the laboratory, please dismantle any circuits or connections that you have made and tidy the workstation. Show your instructor that the screen saver on the computer is the same as when you entered the lab.